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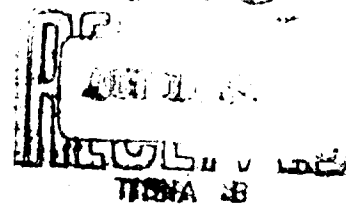
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EFFECT OF EXPOSURE TIME
ON CAVITATION DAMAGE

by

Milton S. Plesset and Robert E. Devine



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Abstract

It has been proposed in some recent publications that the cavitation damage rate decreases markedly in solids after long exposure to cavitation. It has also been proposed that this low rate of cavitation damage is the one with physical significance for the solid. These observations have been made with specimens oscillated sinusoidally in liquids by means of magnetostrictive devices.

In the observations described here it is shown by means of photographs of the cavitation cloud over such specimens that the reduced damage rate results from the very sparse bubble cloud which is formed over the deeply damaged surface. The change in the damage rate therefore has hydrodynamic origin and is not related to a change in the properties of the solid. X-ray analyses show also that the extent of the plastic deformation of a solid with very light damage is the same as for a solid with very heavy damage.

INTRODUCTION

In a recent series of publications by Thiruvengadam and collaborators [1-5]¹ emphasis has been placed on the changes in the rate of cavitation damage with the duration of the exposure time. The cavitation damage process is divided by these writers into four zones which are described as follows: Zone 1 - the incubation or no-weight-loss zone, Zone 2 - the accumulation zone, Zone 3 - the attenuation zone, and Zone 4 - the steady-state zone. Typical graphs which are presumed to show these zones are reproduced in Figs. 1 and 2. These figures are reproduced from Ref. 3; they have also been published in Ref. 5. The important "zone" of cavitation damage is considered in these papers to be zone 4 which is taken to be the region of theoretical significance. The cavitation damage in these experiments was produced by oscillating a specimen immersed in water at an amplitude of the order of 10^{-3} in. at a frequency of approximately 14×10^3 cycles/sec. The accelerations of the specimen are produced by means of a magnetostrictive oscillator.

CAVITATION DAMAGE MEASUREMENTS

We have measured cavitation damage which has been generated in a similar way with a magnetostrictive oscillator. Our equipment, indicated schematically in Fig. 3, has been described in detail in Refs. [6,7] and does not require further description here. We undertook to make measurements similar to those made in Ref. [1-5]. We chose

¹ Number in brackets designate References at the end of the paper.

as the test material 4340 steel. All the specimens were made from the same stock which was annealed and had a Brinell hardness number of 173(3,000 kg scale). It was useful to use annealed specimens since our observations included X-ray analyses. Our measurements were made both with flat-faced and with dished specimens (see Fig. 4). The cumulative weight loss is shown as a function of time of exposure in Fig. 5 and the rate of cavitation damage is shown in Figs. 6 and 7. The data which are given in these latter figures have a general trend similar to that shown by Thiruvengadam and his co-authors. We find that the so-called zone 2 has a much more nearly constant rate of weight loss than indicated by Thiruvengadam. This region corresponds to the "linear" portion in Fig. 5. It is our observation that this region of damage has a more nearly constant rate of weight loss and has a more extended duration when the face of the specimen has been carefully prepared to have a smooth, plane surface. The so-called zone 4 in our measurements does not show a precisely constant rate. It is very clear that the damage rate has fallen to an appreciably lower value than that characteristic of the linear region.

It should be emphasized that in this zone 4, the region of reduced cavitation weight loss rate, the specimen has undergone extensive damage. After this exposure time the face of the specimen has deep, ragged pits which extend inward of the order of 30 to 50 thousandths of an inch being separated by distances of this same order of magnitude, and have widths again of this magnitude (see Fig. 8). It is most difficult to accept the view which has been advanced that this region of damage, which appears after very long exposure times, has a fundamental significance for the

response of the solid to the cavitation. It was shown some time ago [8] that the plastic deformation produced in a solid by cavitation sets in almost immediately upon exposure and, after a relatively short time of the order of seconds or minutes has established a region of cold work which is rather shallow. In the observations of Ref. 8, it was found that this depth of plastic deformation was of the order of only $50\mu^*$. It therefore is to be expected that the behavior found in a heavily damaged surface does not reflect any basic property of the solid when exposed to cavitation. It is to be expected rather that the effect is an incidental, superficial one related to the particular hydrodynamic behavior of an extremely rough specimen as it is oscillated by the magnetostrictive device. That this is indeed the case may be shown by photographic study of the cavitation cloud and by X-ray analyses of the damaged solid. The misinterpretation of the meaning of the change in damage rate with exposure time by the authors of Ref. 1-5 has led them to several erroneous suggestions and conclusions. As has been indicated, theoretical implications for the behavior of the solid have been developed. It has also been proposed that a test procedure using zone 4 should be adopted. Presumably these ideas have contributed to a misunderstanding [3] of the role of corrosion in cavitation damage [7].

PHOTOGRAPHIC OBSERVATIONS OF THE CAVITATION CLOUD

The faces of the specimens used for the damage studies were of two kinds. The one kind had flat faces exposed to the cavitation cloud,

* $1\mu = 1 \text{ micron} = 10^{-4} \text{ cm}$).

and the other kind had "dished" faces for which the flat surfaces were surrounded at the perimeter by a wall approximately 0.030 in. high and 0.020 in. thick. Both kinds of specimens showed the same general behavior.

Pictures were taken of the cavitation cloud with an exposure time of 2 microseconds which is short compared with the 70 microsecond period with which the specimens were oscillated by the magnetostrictive driver. The short exposure was obtained by means of a pulse which fired an FX 2 flash lamp. The pulse was phased with the 14 kc/sec magnetostrictive driving voltage so as to photograph the bubble cloud at its maximum over the specimen face. Figure 9 shows the maximum bubble cloud over a dished specimen before visible damage has developed; this bubble cloud occurs in the so-called zone 1. Figure 10 shows the maximum bubble cloud over a dished specimen when the cavitation damage is taking place in the region of linear weight loss; this region is the so-called zone 2 of Thiruvengadam, et al. There is no essential difference between the bubble cloud in these two regions. Figure 11 shows the maximum bubble cloud over a dished specimen which has been heavily damaged; this is the so-called zone 4, or the "steady-state" zone. It is very evident that the bubble cloud is considerably reduced in intensity as a consequence of hydrodynamic damping effects over the deeply damaged surface. It is apparent that the reduced rate of weight loss is a result of the reduced density of the bubble cloud. Figures 12, 13, and 14 show that flat-faced specimens have the same behavior as the dished specimens.

The hydrodynamic effect on the bubble cloud of the deeply pitted face may be very clearly shown in other ways. After a specimen had

reached the so-called zone 4 one half of the face was smoothed off and the remaining half was left unchanged as shown in Fig. 15. Figure 16 is a flash photograph of the cavitation cloud over the face of such a specimen; it shows the great difference in the cavitation cloud for the surface in these two conditions. The effect of holes in a surface on the cavitation cloud may also be illustrated by making small holes in an undamaged flat surface as illustrated in Fig. 17. These holes were made electrolytically with a bundle of fine wires; the holes are approximately 0.019 in. in diameter, 0.050 in. in depth, and approximately 0.015 in. apart. Figure 17 shows the maximum bubble cloud over the specimen face as the specimen is oscillated sinusoidally by the magnetostrictive oscillator. The bubble cloud is clearly very sparse compared with that over a specimen with smoother surface.

X-RAY ANALYSIS OF CAVITATION DAMAGE

Laue X-ray diffraction patterns were obtained from 4340 steel specimens before exposure to cavitation and after exposure to cavitation for various times. The X-ray beam was circular in cross section with a diameter of 0.030 in. and was well collimated. The X-ray line used was the Cobalt K_{α} line which has a wavelength of 1.790 Angstroms. The beam was directed normally on the face of the specimen, and the back-reflected diffraction pattern was recorded on photographic film. The maximum depth of penetration of these X-rays into the specimen material is about 25μ ; the important contribution to the diffraction pattern comes from the first 10μ below the specimen surface.

Figure 18 shows the diffraction pattern of a 4340 specimen before

exposure to any cavitation; the sharp spots are indicative of a well-defined crystal structure. The progressive smearing of the spots into a continuous ring upon exposure to cavitation is illustrated in the series of patterns shown in Fig. 19 and the distortion of the structure is thereby demonstrated. Loss in definition of the spots is already evident in Fig. 19a which corresponds to only 10 seconds exposure to cavitation. It is evident that the plastic deformation of the crystal structure begins immediately upon exposure to cavitation. The plastic deformation sets in before the surface shows damage which is evident from optical examination. Plastic deformation of the depth available to examination by the X-rays appears to be fairly complete in 5 minutes and is clearly complete in 30 minutes to 1 hour of exposure to the cavitation. The depth of penetration of the plastic deformation after 1 hour exposure to cavitation may be found by removal of surface layers by means of electrolytic polishing until the crystal pattern is restored. The X-ray patterns after successive removals of surface layers are shown in Figures 20 a, b, and c. It is evident that the removal of 31μ from the damaged surface does not restore the sharp spot pattern completely. It is, however, restored completely after 46μ has been removed.

A question of concern remains whether the depth of plastic deformation changes with the duration of the cavitation exposure. More particularly, we wish to determine whether periods of exposure to cavitation which are longer than 1 hour give a different depth of plastic deformation. Figure 21 shows that the sharp spot pattern is restored for a specimen which has been exposed to cavitation for 2 hours when 41μ of the surface has been peeled away. A more detailed series is shown in

Figs. 22a-d which gives the results of the X-ray analysis for a specimen which was exposed to cavitation for 10 hours. As Fig. 22d shows, the sharp spot pattern is re-established when 48μ is removed from the surface. Similar results are found in the series shown in Figs. 23a, b, and c, for a specimen which has been exposed to cavitation for 18 hours. The sharp spot pattern of the undistorted crystal structure is obtained after removal of 47μ from the surface. It is also of interest to observe that, before any of the damaged surface has been removed, the plastic deformation does not appear to vary over a range of exposure times from 30 minutes to 18 hours. This behavior is shown in Figs. 19e, 19f, 22a, and 23a.

CONCLUSION

X-ray diffraction patterns show that plastic deformation of the structure of a solid exposed to cavitation begins essentially immediately upon exposure to cavitation. When cavitation damage has been well established, the depth of the deformation of the structure does not change even after appreciable surface erosion has taken place. The decrease in cavitation damage rate after long exposures which has been discussed by some investigators, who used specimens oscillating in the cavitating liquid, is shown to be an incidental hydrodynamic effect. Photographic examination of the bubble cloud over a severely damaged specimen oscillating in a cavitating liquid demonstrates that the cavitation cloud is much more sparse than it is over a more uniform specimen.

Acknowledgments

The authors wish to thank Professor Pol Duwez for advice and suggestions regarding the X-ray analysis procedure. Professor David Wood furnished valuable guidance in the annealing process which was used to prepare the specimens used. The authors are also indebted to Mr. Frank G. Youngkin for his valuable assistance in obtaining the X-ray diffraction patterns.

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4. A. Thiruvengadam and Sophia Waring, "Mechanical Properties of Metals and Their Cavitation Damage Resistance", Tech. Rep. 233-5, Hydronautics, Inc. June 1964.
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6. M. S. Plesset, "On Cathodic Protection in Cavitation Damage", J. of Basic Eng., Vol. 82, Dec. 1960, pp. 808-820.
7. Milton S. Plesset, "The Pulsation Method for Generating Cavitation Damage", J. of Basic Eng. Vol. 85, Series D, No. 3, pp. 360 - 364, Sept. 1963.

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8. M. S. Plesset and A. T. Ellis, "On the Mechanism of Cavitation Damage", Trans. ASME, Vol. 77, 1955, pp. 1055 - 1064.

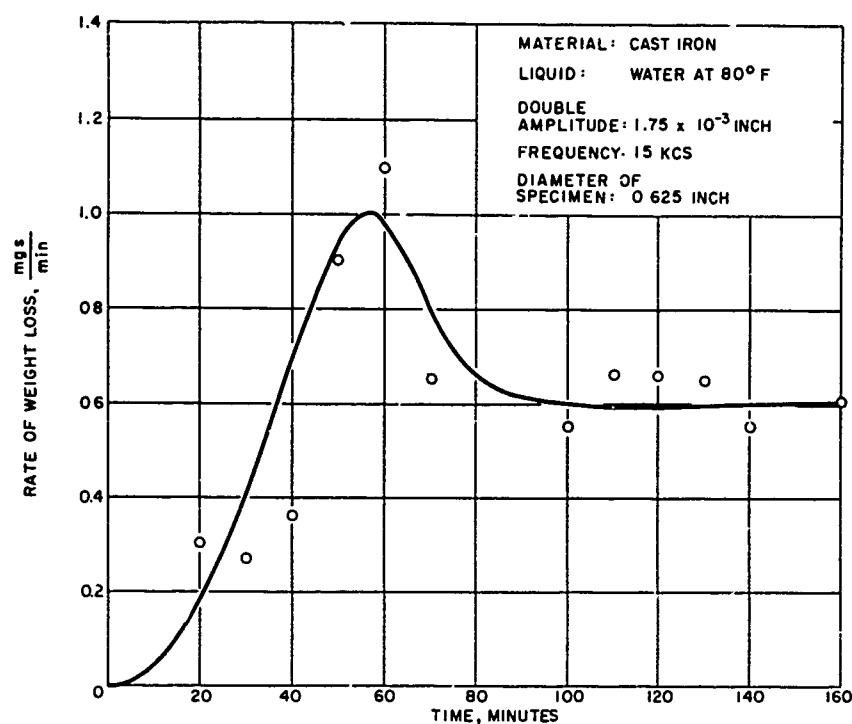


Figure 1 - Rate of cavitation weight loss with "zones of cavitation" as described by Thiruvengadam and Preiser (Refs. 3 and 5).

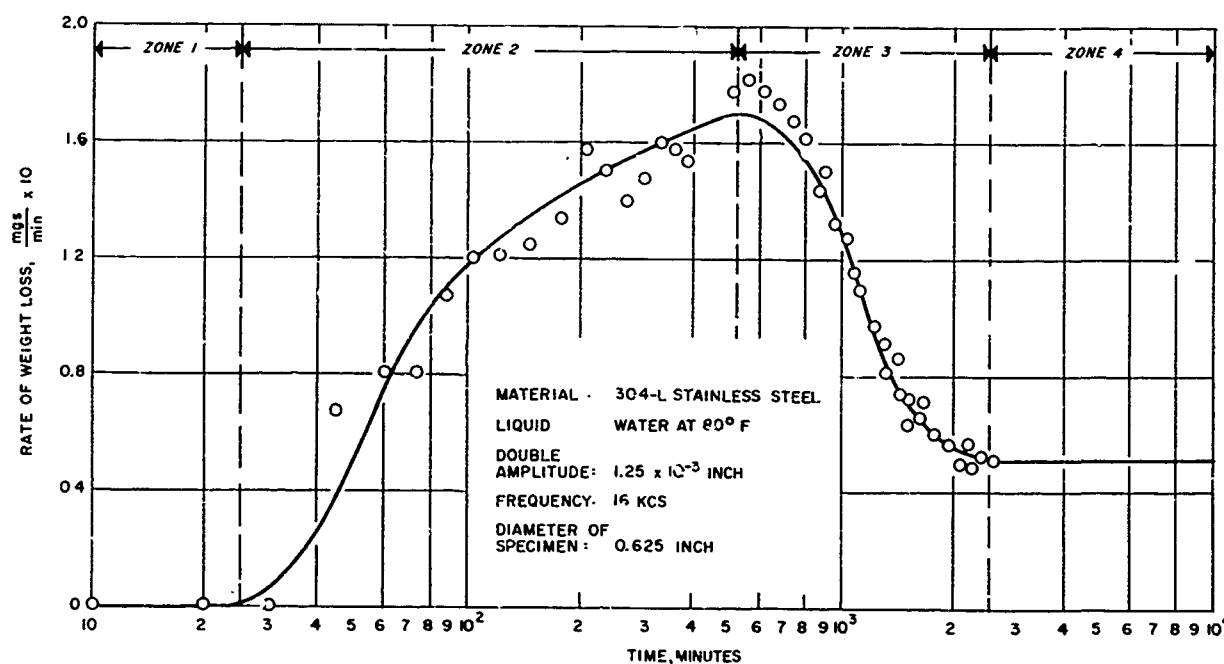


Figure 2 - Rate of cavitation weight loss as given by Thiruvengadam and Preiser (Refs. 3 and 5).

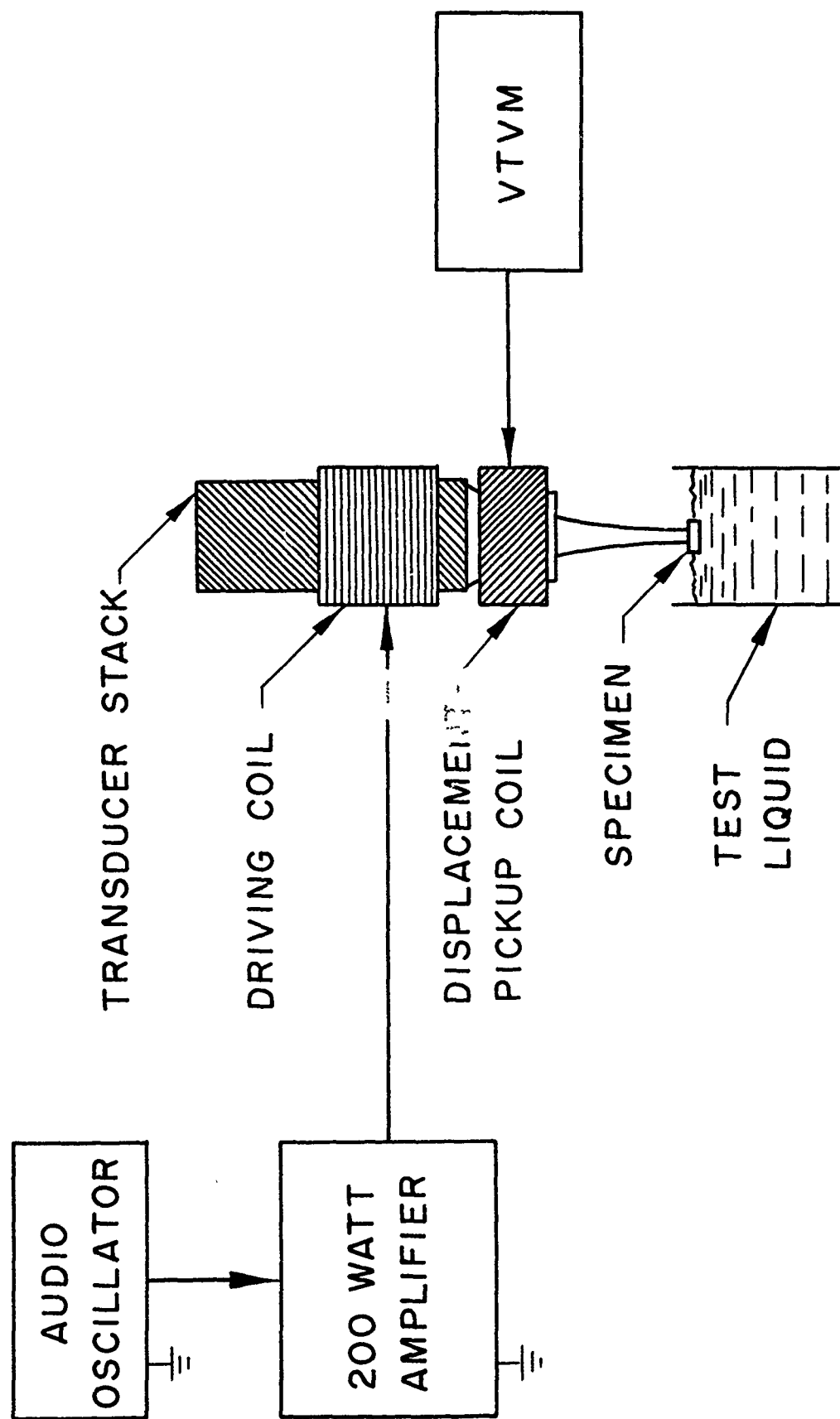


Figure 3 - Block diagram of magnetostrictive oscillator and associated equipment as used in cavitation damage experiments at C.I.T.

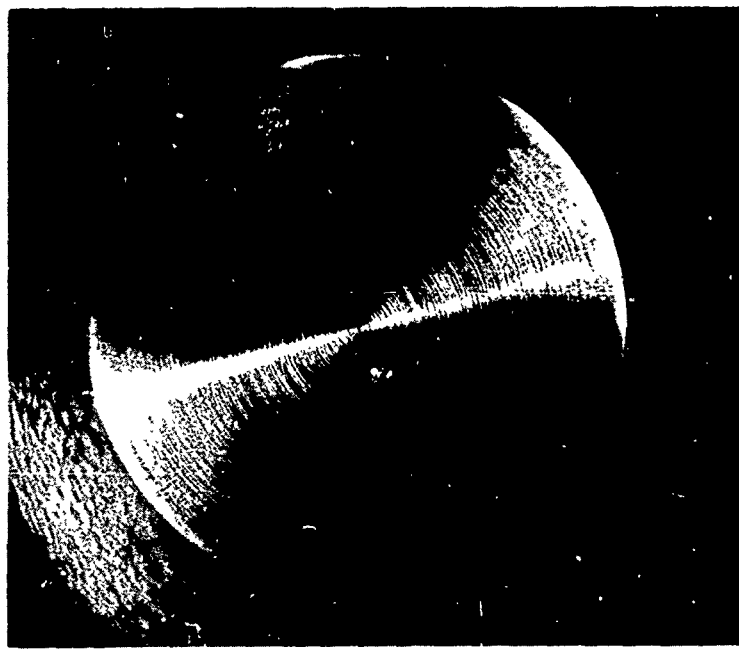


Figure 4(a) - Photograph of flat specimen
before exposure to cavitation.

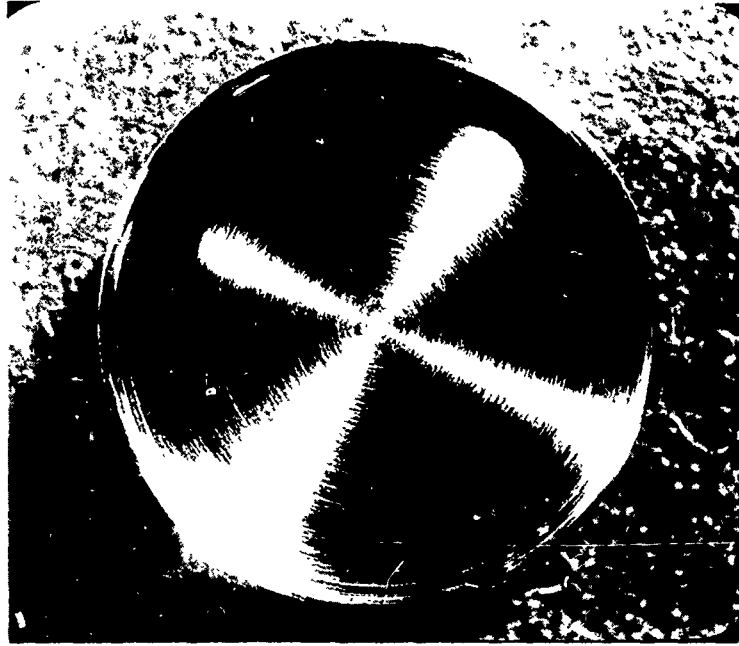


Figure 4(b) - Photograph of dished specimen
before exposure to cavitation.

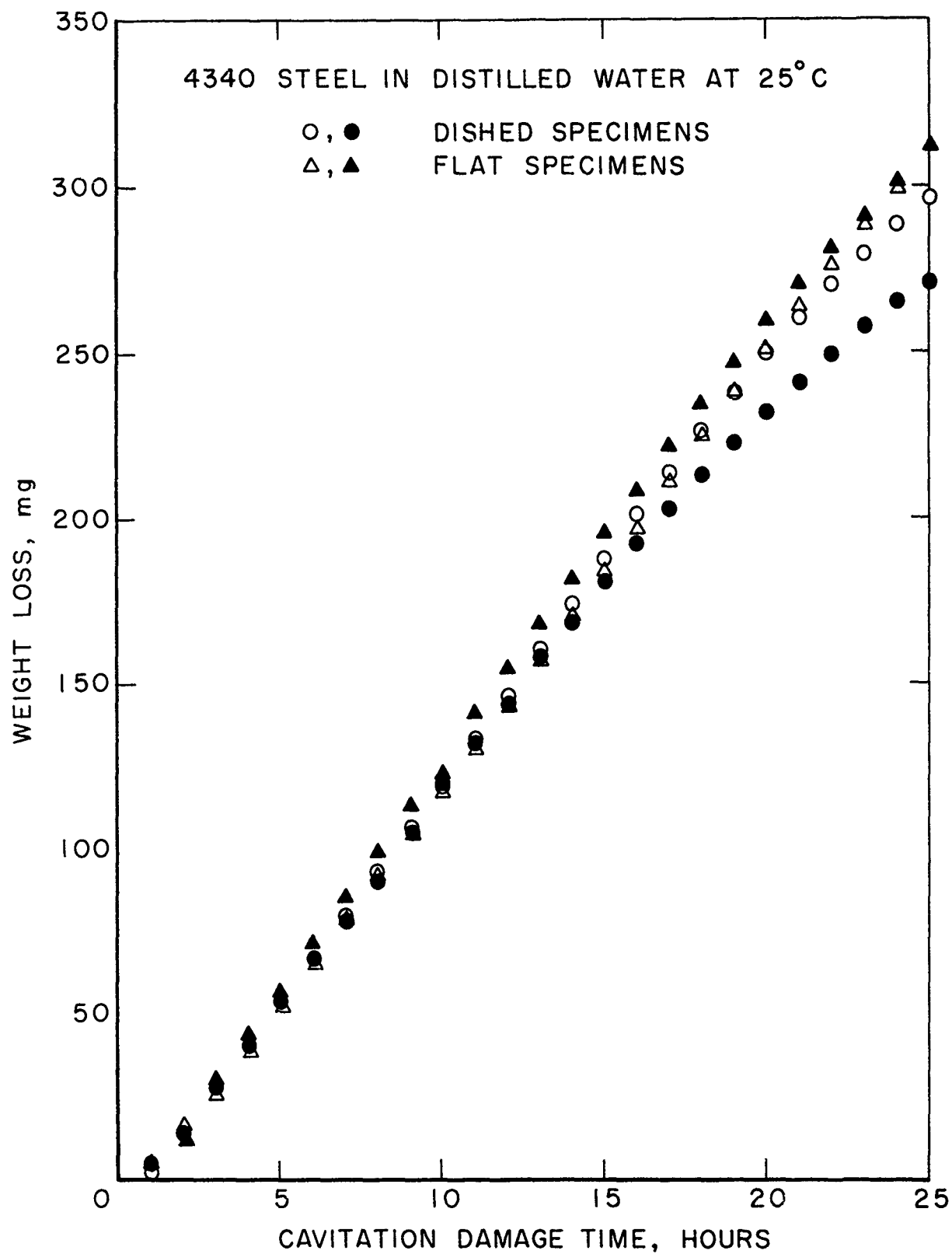


Figure 5 - Cumulative cavitation weight loss in milligrams as a function of cavitation exposure time in hours for 4340 steel, Brinell hardness number 173.

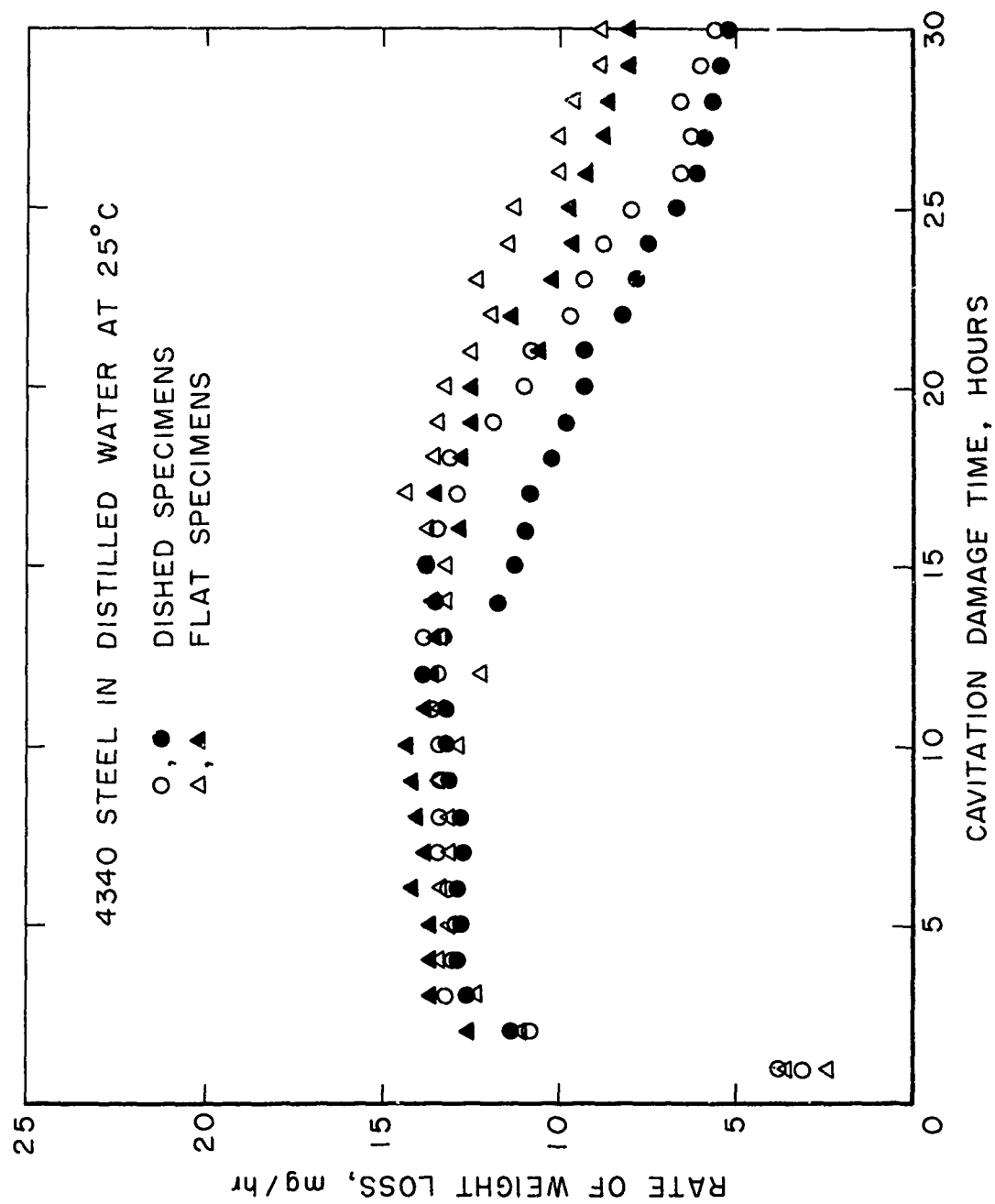


Figure 6 - Rate of cavitation damage weight loss in milligrams per hour as a function of cavitation damage time in hours for 4340 steel.

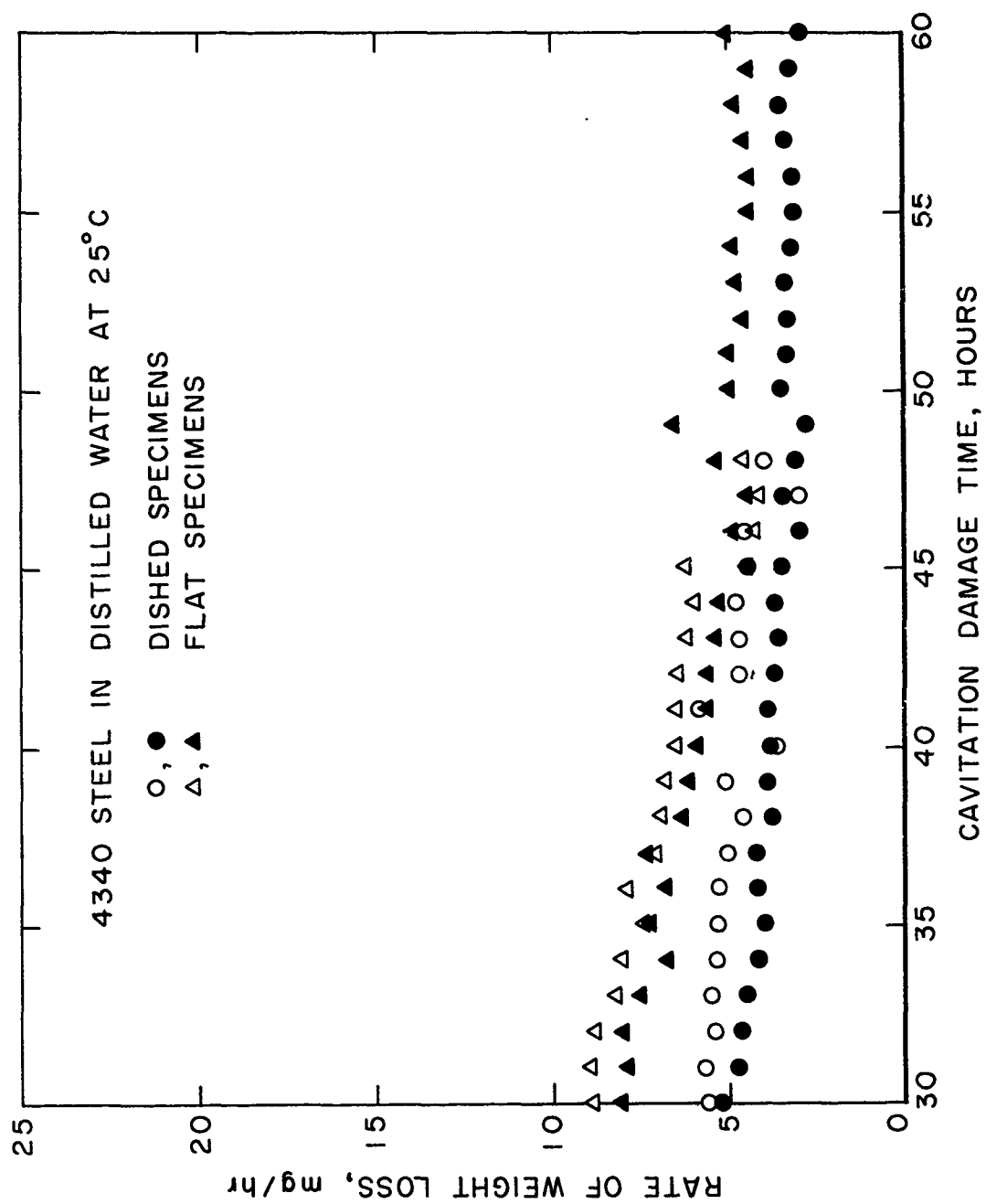


Figure 7 - Continuation of Fig. 6, which gives rate of cavitation weight loss for long exposure times.



Figure 8 - Photograph of 4340 steel after
long exposure to cavitation.
The specimen is in "zone 4".

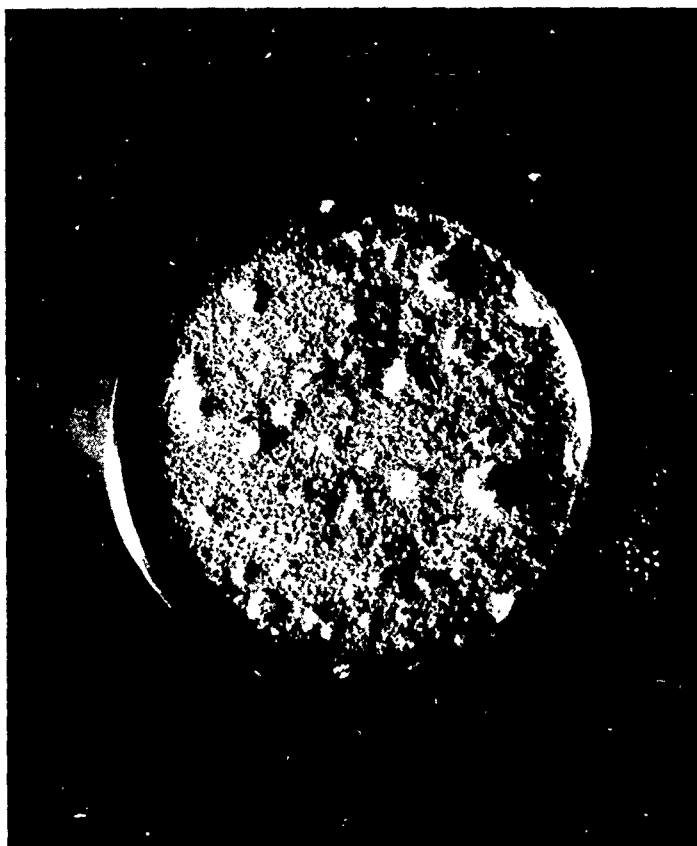


Figure 9 - Photograph of maximum cavitation cloud over dished 4340 specimen before appreciable exposure to cavitation damage ("zone 1"). Photographic exposure time 2 microseconds.

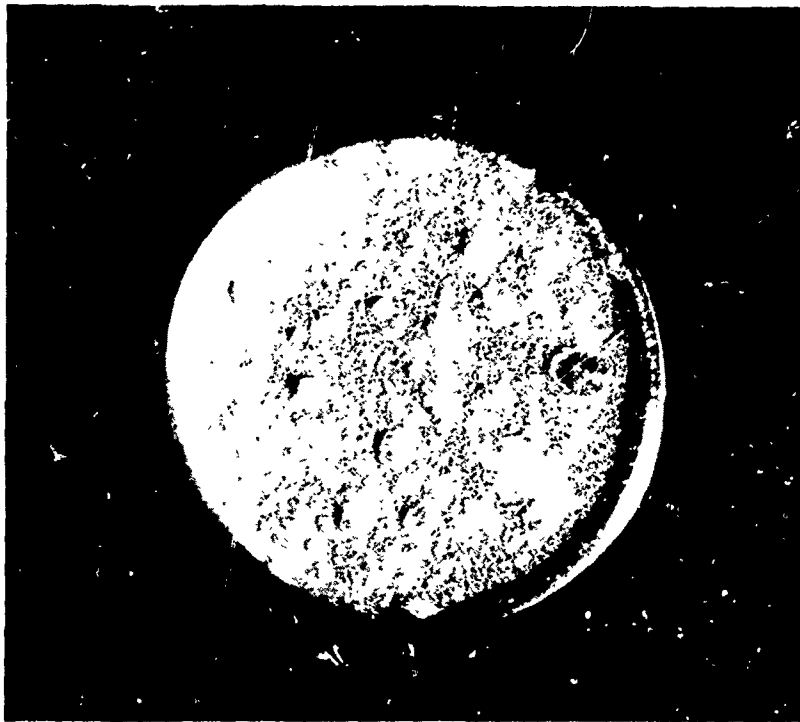


Figure 10 - Photograph of maximum cavitation cloud over dished 4340 specimen in linear weight loss region ("zone 2"). Photo raphic exposure time 2 micro-seconds.



Figure 11 - Photograph of maximum cavitation cloud over dished 4340 specimen after long exposure to cavitation ("zone 4"). Photographic exposure time 2 microseconds.

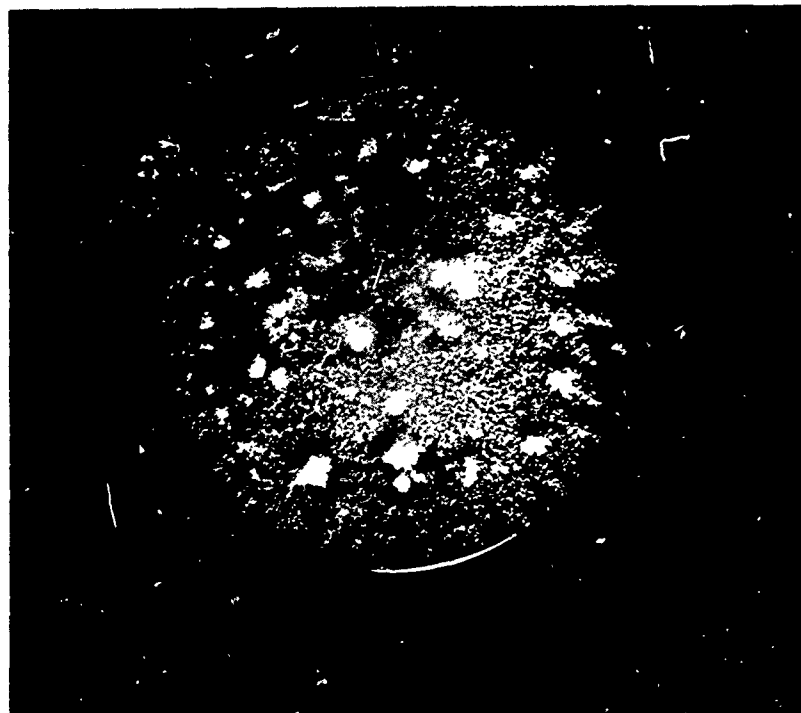


Figure 12 - Photograph of maximum cavitation cloud over flat 4340 specimen before appreciable exposure to cavitation damage ("zone 1"). Photographic exposure time 2 microseconds.

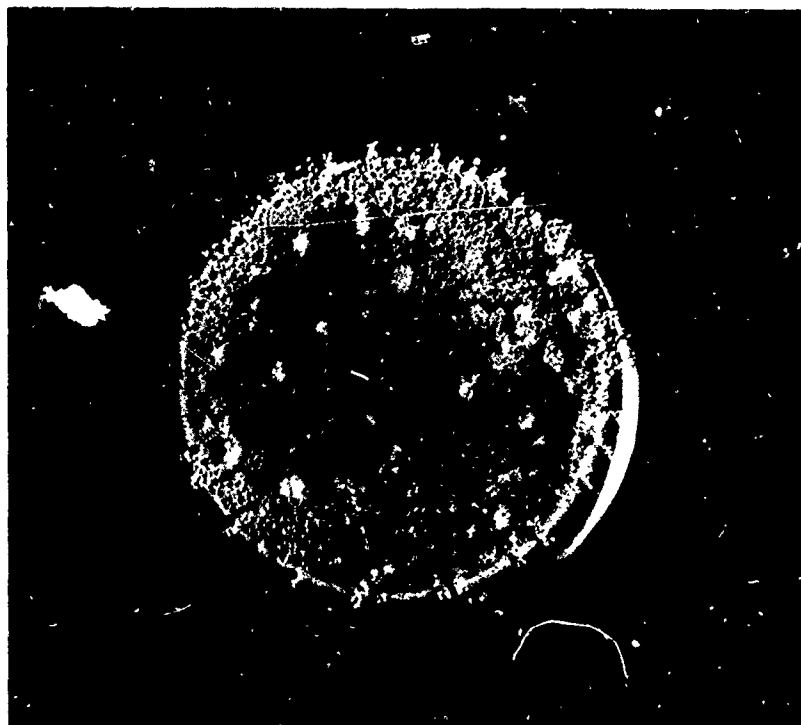


Figure 13 - Photograph of maximum cavitation cloud over flat 4340 specimen in linear weight loss region ("zone 2"). Photographic exposure time 2 microseconds.



Figure 14 - Photograph of maximum cavitation cloud over flat 4340 specimen after long exposure to cavitation ("zone 4"). Photographic exposure time 2 microseconds.

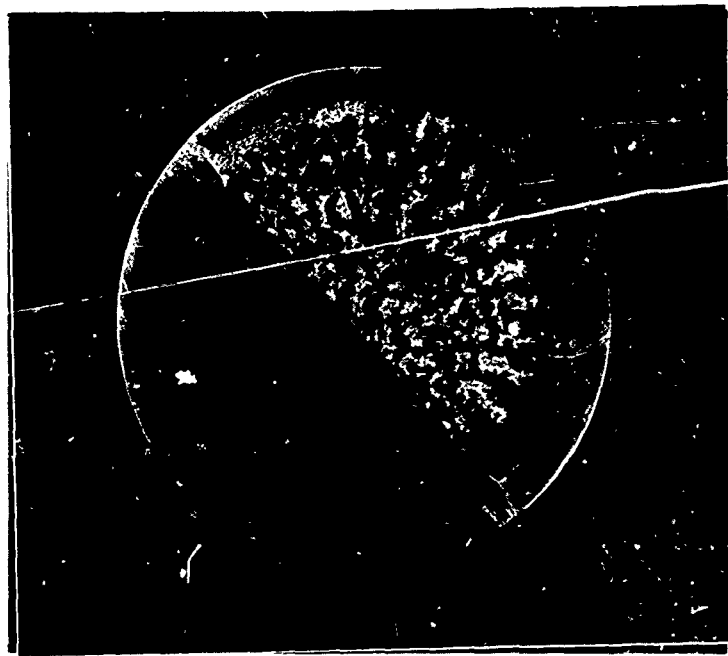


Figure 15 - Flat-faced 4340 specimen with one half of the face ground and polished smooth; the remaining half of the face has been left as it was after long exposure to cavitation ("zone 4").



Figure 16 - Photograph of maximum cavitation cloud over the specimen with the face as shown in Fig. 15. Photographic exposure time is 2 microseconds.

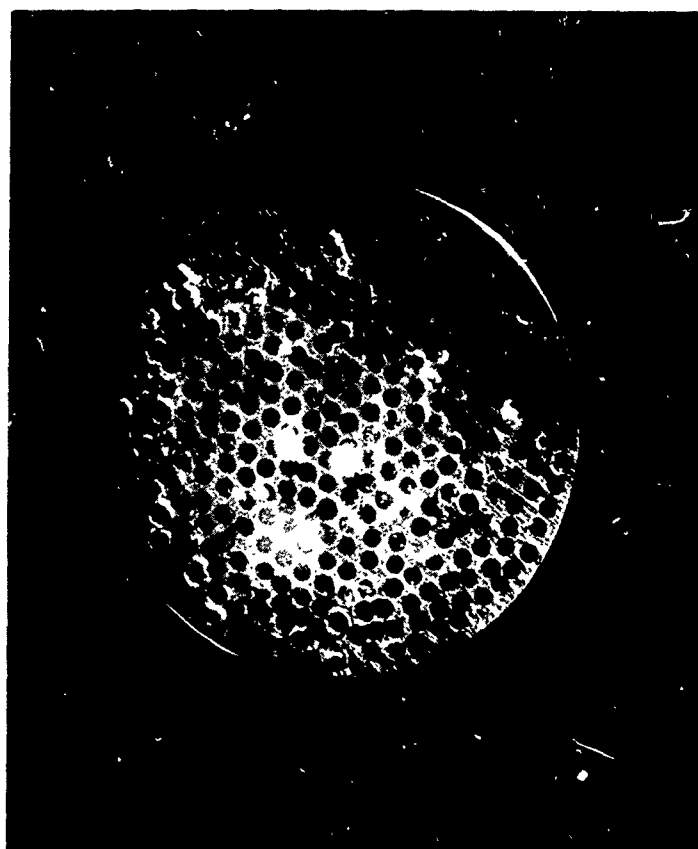


Figure 17 - Photograph of maximum cavitation cloud over undamaged specimen with cylindrical holes. The holes are approximately 0.019 in. in diameter and 0.050 in. in depth. Photographic flash duration 2 microsecond.

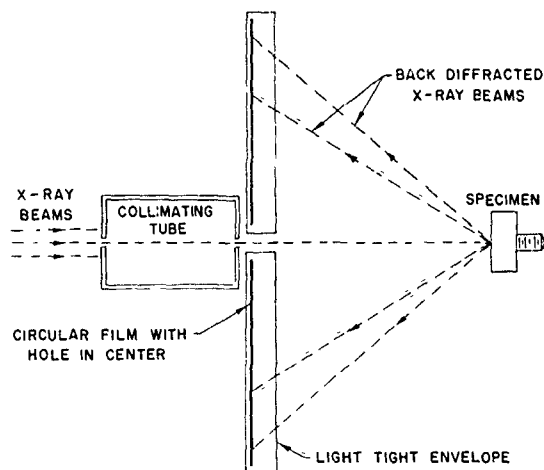


Figure 18(a) - Diagram of arrangement for obtaining X-ray diffraction pattern.

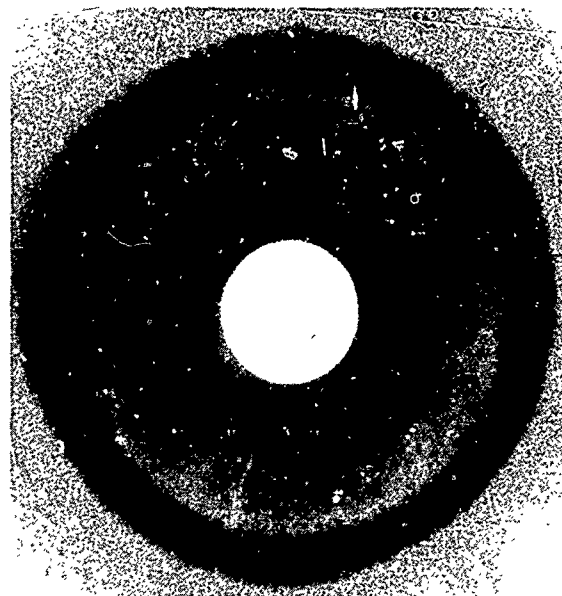


Figure 18(b) - X-ray Laue diffraction pattern from an undamaged 4340 specimen. The well defined spots show the regular crystal structure of the material.

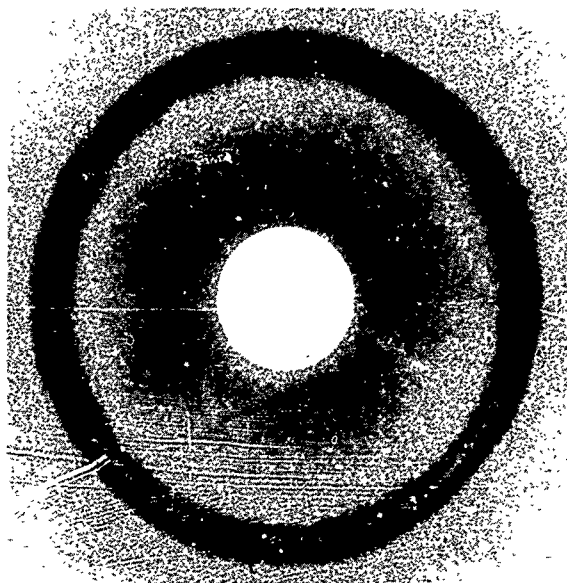


Figure 19(a) - The X-ray Laue diffraction pattern of the specimen after a 10 second exposure to cavitation.

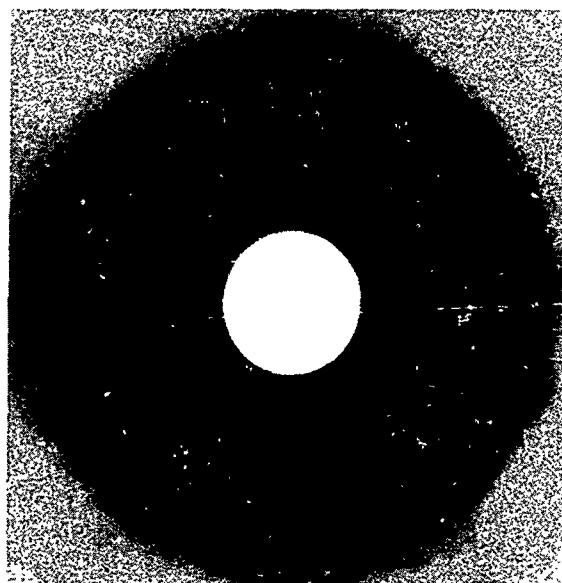


Figure 19(b) - The X-ray Laue diffraction pattern of the specimen is shown after exposure of one minute to cavitation.

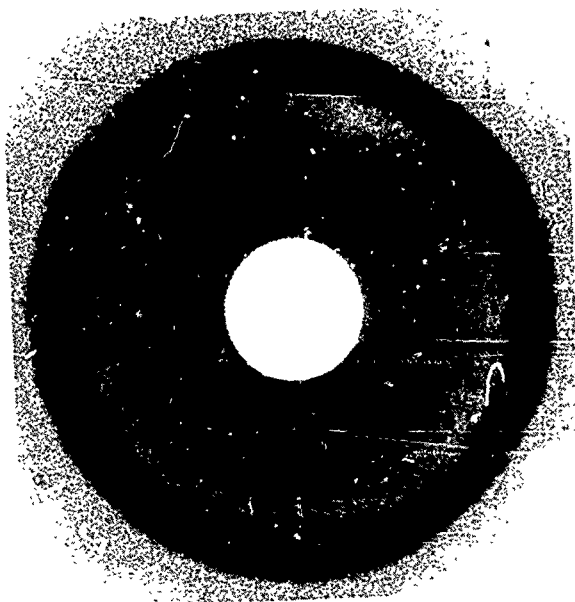


Figure 19(c) - The X-ray Laue diffraction pattern after exposure of five minutes to cavitation.

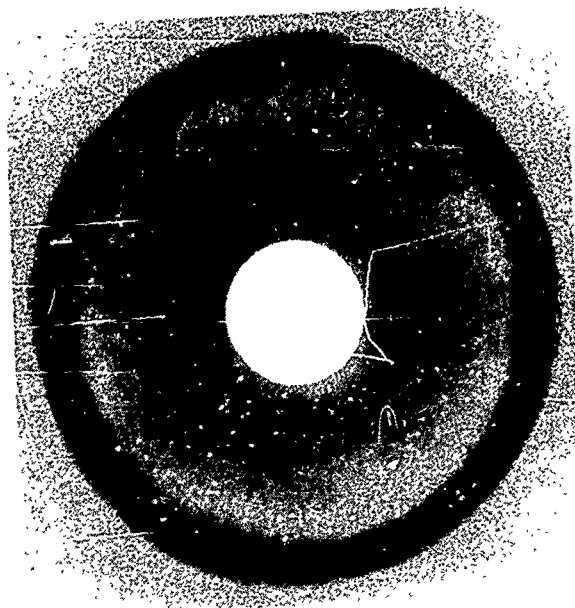


Figure 19(d) - The X-ray Laue diffraction pattern is shown after 15 minutes exposure to cavitation.

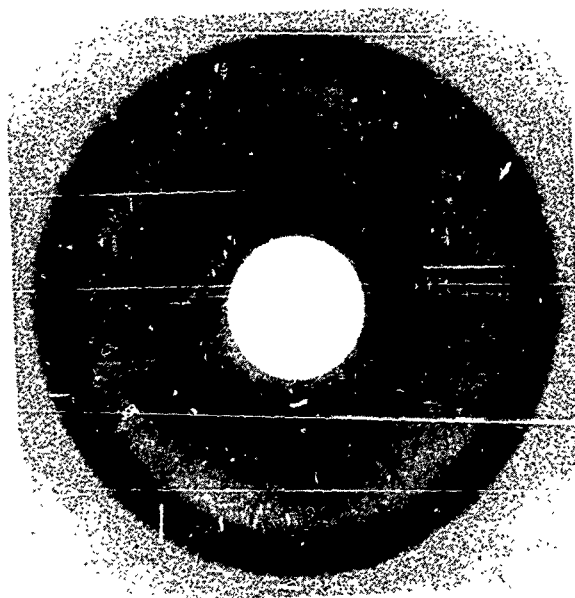


Figure 19(e) - The X-ray Laue diffraction pattern is shown after 30 minutes exposure to cavitation.

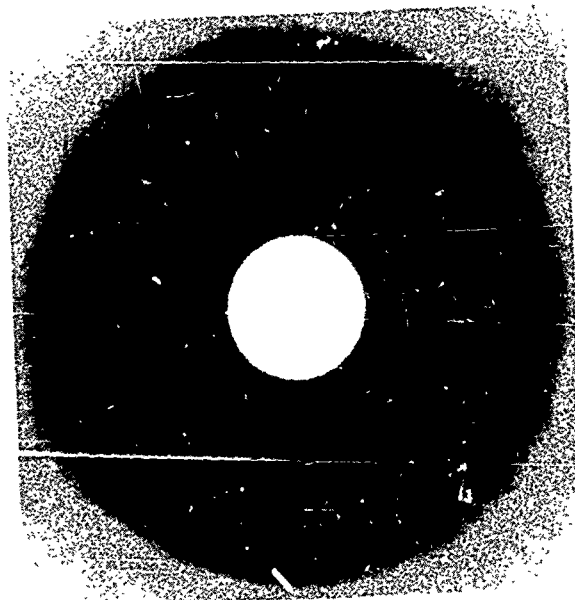


Figure 19(f) - The X-ray Laue diffraction pattern is shown after one hour exposure to cavitation.

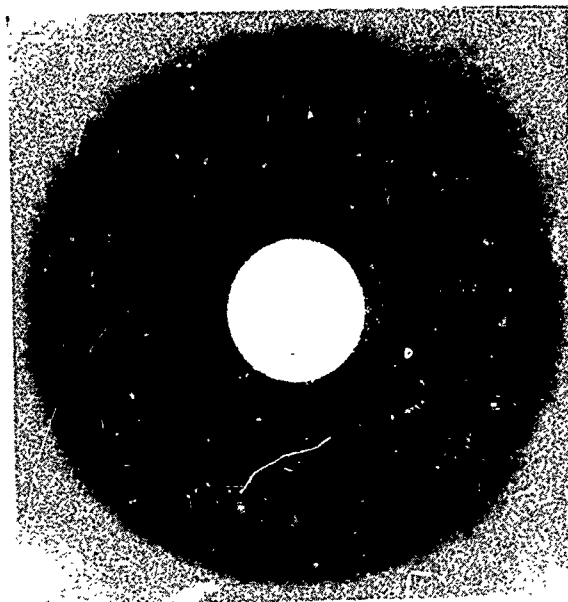


Figure 20(a) - The X-ray Laue diffraction pattern is shown for a specimen exposed to cavitation damage for one hour. Six microns (μ) of the surface have been peeled off by electrolytic polishing.

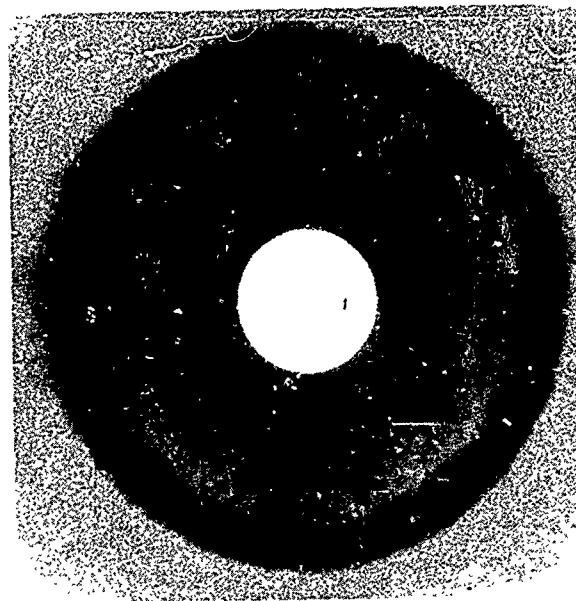


Figure 20(b) - The X-ray Laue diffraction pattern is shown for a specimen exposed to cavitation damage for one hour. Thirty-one μ of the surface have been peeled off by electrolytic polishing.

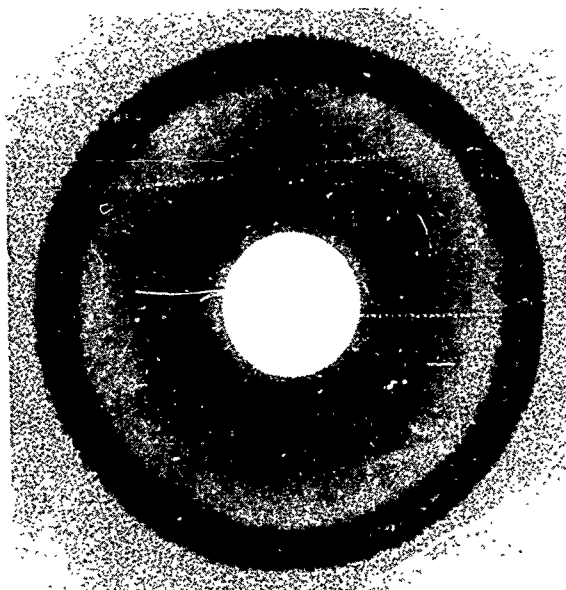


Figure 20(c) - The X-ray Laue diffraction pattern is shown for a specimen exposed to cavitation damage for one hour. Forty-six μ of the surface have been peeled off by electrolytic polishing.

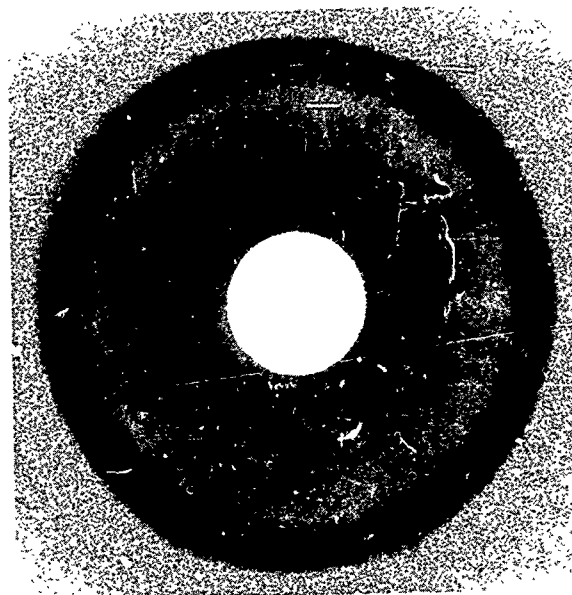


Figure 21 - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for two hours, 41 μ have been removed by electrolytic polishing.

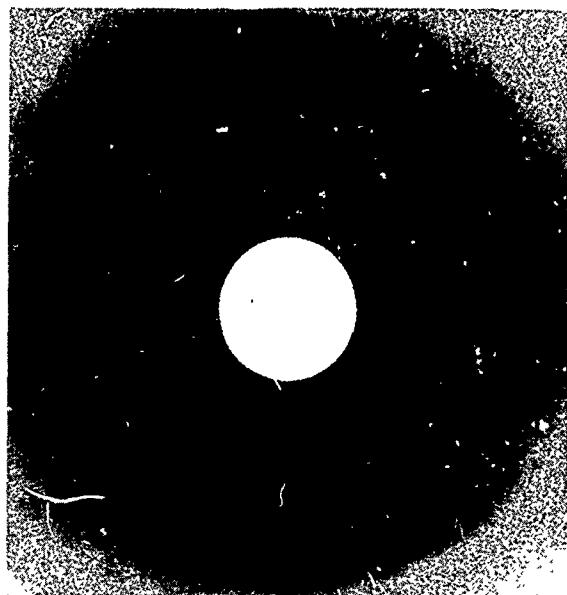


Figure 22(a) - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for 10 hours.

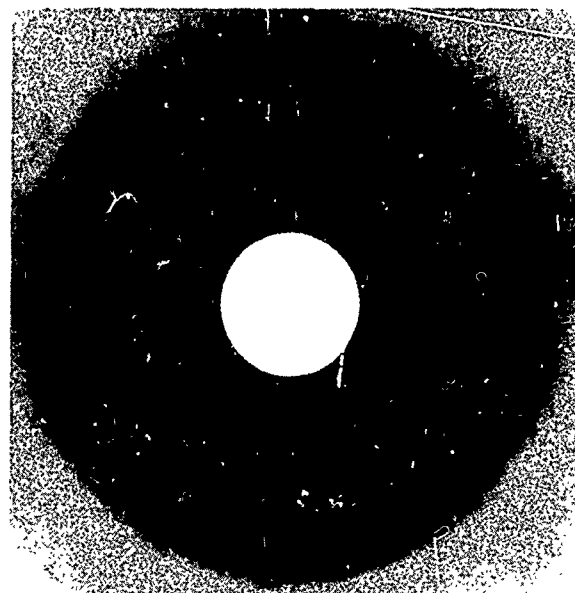


Figure 22(b) - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for 10 hours, 6μ have been removed by electrolytic polishing.

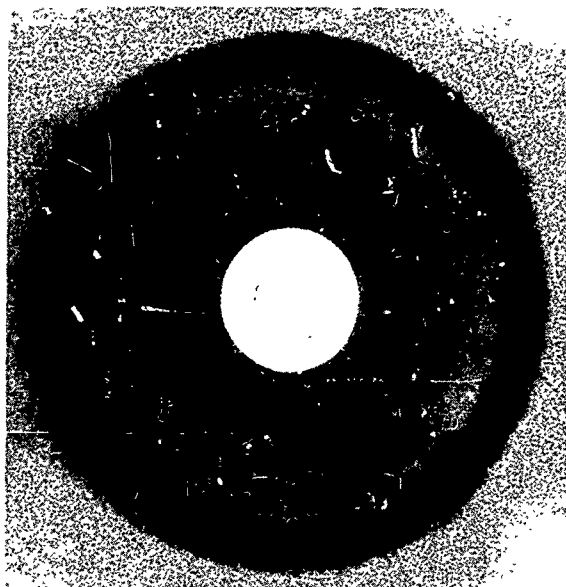


Figure 22(c) - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for 10 hours, 32μ have been removed by electrolytic polishing.

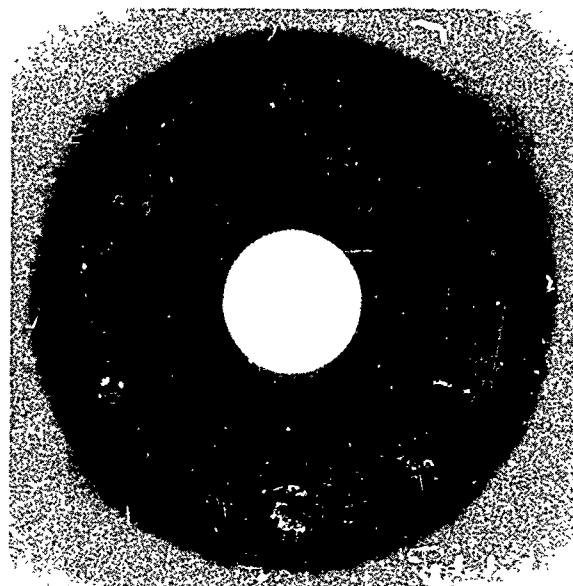


Figure 22(d) - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for 10 hours, 48μ have been removed by electrolytic polishing.

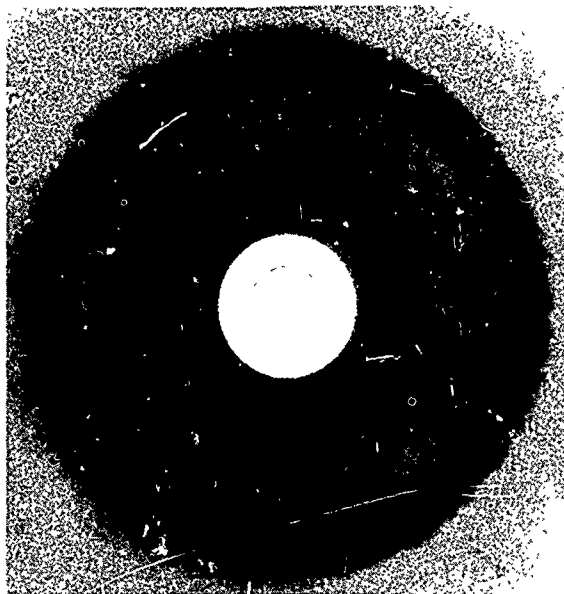


Figure 23(a) - The X-ray Laue diffraction pattern is shown for a specimen which has been exposed to cavitation for 10 hours.

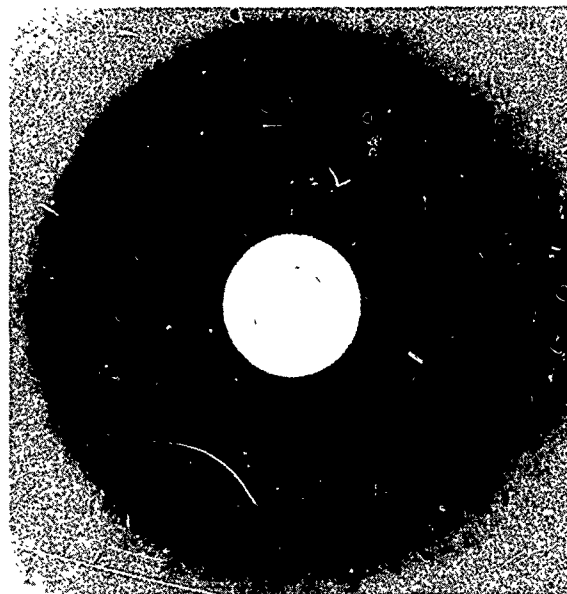


Figure 23(b) - The X-ray Laue diffraction pattern is shown for a specimen exposed to cavitation damage for 18 hours, 33 μ have been removed from the surface by electrolytic polishing.

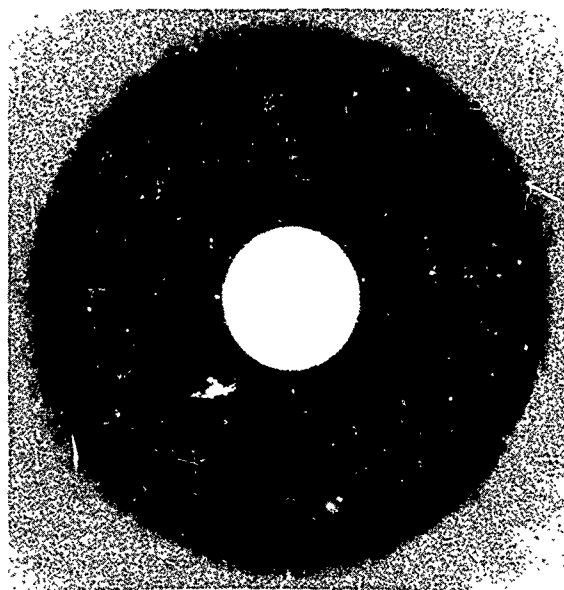


Figure 23(c) - The X-ray Laue diffraction pattern is shown for a specimen exposed to cavitation damage for 18 hours, 47 μ have been removed from the surface by electrolytic polishing.